Appendix F:

The Value of Electromagnetic Fields Research

Decision Insights, Inc.

Draft

The Value of Electromagnetic Fields Research

Detlof von Winterfeldt
School of Policy, Planning, and Development
University of Southern California
Los Angeles, CA 90089

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Abstract

For almost twenty years researchers have attempted to establish a link between electromagnetic fields (EMF) exposure and several health effects, including leukemia, brain and breast cancer, and Alzheimer's disease. By and large, the results of this effort have not conclusively shown that EMF exposure poses a health hazard. The question thus arises, whether it is worth spending additional money on EMF research? The answer to this question depends on many factors, including the probability and seriousness of possible health effects due to EMF exposure, the probability of reaching conclusive results from future EMF research, the cost and effectiveness of mitigation, and other social costs of the EMF controversy.

To determine the value of future EMF research, a value-of-information analysis was conducted within a decision analysis framework. The probability of a health hazard and the probabilities of positive and negative research breakthroughs are important parameters of the decision tree model. The research breakthrough probabilities were expressed as functions of the research funding level. The probabilities and consequences in the decision tree were fully parameterized, so that the user can specify and explore numerous scenarios. A typical scenario assumed a 10% probability that there are serious health effects with 1,000 annual cancer fatalities, $50 billion in mitigation costs, and $30 billion in other social costs including losses of property values.

The value of research was quite high for all reasonable scenarios. Optimal research funding levels ranged from a few million dollars to over one hundred million dollars per year. To stop special EMF research funding was preferred if

1) the cost of mitigation was very small compared to the combined health effects and social costs;
2) the cost of mitigation was equal to or higher than the combined health effects and social costs;
3) the probability of an EMF health hazard was extremely small;
4) eliminating special EMF research funding would substantially reduce the social costs associated with law suits and power line siting controversies.

On balance, however, the robust conclusions of the decision analysis presented in this paper is that special EMF research funding should be continued at a high level, and should possibly increased from current levels. As long as the stakes are high and the chances of a hazard are in the order of 10% or higher, it is worth to pursue the elusive research breakthrough.

Introduction

In 1979 Wertheimer and Leeper published an important study that suggested a link between childhood leukemia and the proximity of living near some types of electrical power lines. Since then, numerous studies were conducted to prove or disprove that exposure to electromagnetic fields (EMFs) from power lines and other sources contribute to increased cancer and other health risks. Major sponsors of this research were the Electric Power Research Institute and the National Institute of Environmental Health Science (NIEHS), along with several state organizations. At its peak, the US funding for EMF research alone was about $25 million per year.

Twenty years and some $200 million in research expenses later, the question of whether or not EMFs pose a health hazard can still not be answered conclusively. A review by the National Academy of Sciences stated that “Based on a comprehensive evaluation of published studies...., the conclusion of the committee is that the current body of evidence does not show that exposure to these fields presents a human-health hazard.” (National Research Council, 1996, p. 1). In particular, while epidemiological finding continue to cause concern, the search for a biological mechanism has remained elusive.

An obvious question is: Is it worthwhile to spend more money on EMF research, given that the past twenty years and substantial research investments have not resolved the issue? The answer to this question depends on many factors, including the probability that there truly is a health hazard, the chances of a research breakthrough, the cost of research, the cost of mitigation, and other social costs of the EMF issue.

To explore the value of continued EMF research, we constructed a decision analysis model and determined the value of research within this model (for references to decision analysis, see Clemen, 1991; Raiffa, 1968; von Winterfeldt and Edwards, 1986). Since many model parameters are uncertain, the model was fully parameterized to support extensive sensitivity analyses and to allow the users to investigate specific scenarios. In particular, the probability of health hazard, the magnitude of health effects, the probability of a research breakthrough, and the cost of mitigation were explored for a large range of possible values.

Section 2 describes the structure, input parameters and ranges of the decision analysis model. Section 3 described the results for several scenarios. Section 4 provides numerous sensitivity analyses. Section 5 draws some conclusions for future EMF research policy.

The Decision Analysis Model

According to a key decision analysis principle, information is valuable only if it can change subsequent decisions and their consequences. For example, if you are living near a powerline, information about a health hazard from EMFs may cause you to move to avoid the possible health consequences. If knowing whether or not an EMF health hazard exists would not cause you to change any decisions, this information would not be valuable. On a societal level, EMF research is valuable only to the extent that it can change societal mitigation decisions. A major modeling task therefore was to link possible research results with decisions on whether to mitigate or not, and to estimate the costs of mitigation.

Another major task was to model the probabilistic relationships between the existence of non-existence of a health hazard, the possibility of a research breakthrough, the research funding level, and the time it takes to achieve a breakthrough. Most researchers would assign a non-zero probability to the proposition that EMFs pose a health hazard, even though the probability and the degree of seriousness would vary from one researcher to another. Most researchers would also agree that the probability of achieving a breakthrough in the next twenty is less that 1, especially considering that we already spent 20 years of research without a breakthrough.

The decision tree. Figure 1 shows the decision tree that embodies these thoughts. At the root (decision) node, two alternatives are considered: 1) Continue funding special EMF research at an annual level of $R (e.g., at $20 million per year) vs. 2) discontinue special funding of EMF research except for funds available through basic research funding agencies (e.g., $1 million per year). Following this decision are three possible events: The research produces a positive breakthrough, a negative breakthrough, or it remains inconclusive. A positive breakthrough establishes unequivocally that there is a

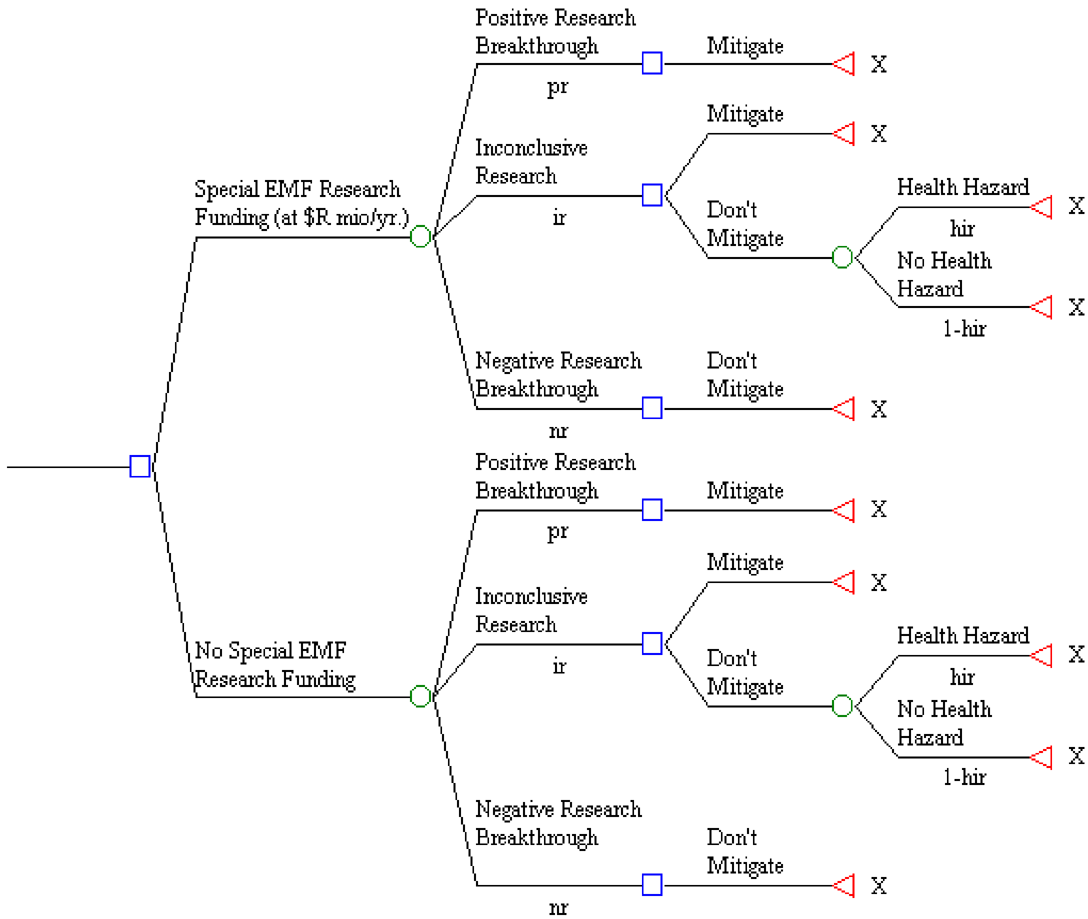


Figure 1: The Decision Tree to Determine the Value of EMF Research

health hazard, without the possibility of a false alarm. Similarly, a negative breakthrough establishes unequivocally that there is no health hazard (for example, by finding a confounder in all previous epidemiological studies), without the possibility of a false rejection. Note that for these conditions to hold, a positive breakthrough can only occur, if there is a health hazard, a negative breakthrough can only occur if there is none. If there is neither a positive nor a negative breakthrough, the research will remain inconclusive.

In the event of a positive breakthrough, the model forces a mitigation decision. Depending on the seriousness of the hazard, this mitigation could involve undergrounding a significant proportion of transmission and distribution lines and to fix wiring and grounding systems in homes. The option not to mitigate in the face of a positive breakthrough could also be considered, if the mitigation costs are substantially higher than the health and other social costs of EMF exposure. However, it is unlikely that society would allow this option, once EMFs have been established as a serious health hazard.

In the event of a negative breakthrough, the only reasonable decision is not to mitigate.

In the event of continued inconclusive research, both mitigation and non-mitigation options have to be weighed in light of the probability of a health hazard, the seriousness of the hazard, the cost of mitigation, and other social costs. For example, if the mitigation costs are high, the health risks and other social costs are low, it may be advisable not to mitigate at this decision node in the tree.

The nodes and branches of the tree following the decision to provide special EMF funding are the same as those following the decision not to provide special EMF funding. However, the probabilities and some consequences differ.

Probabilities. In the decision tree, the results of future research are determined first. In the case of a positive or negative breakthrough, the issue of whether or not a hazard exists is resolved. If the research is inconclusive, the ultimate status of a hazard remains uncertain. This decision tree structure suggests to assess the unconditional probabilities of the three possible research outcomes first, then to assess the conditional probabilities of a hazard, depending on the research outcomes.

In practice, it more natural to reverse the order of conditioning: First, we determine the unconditional probability of hazard vs. no hazard, and second, we determine the conditional probabilities of research outcomes, given a hazard or no hazard. Using Bayes' theorem and simple probability calculus, the probabilities required for the decision tree can then be calculated.

The probability of a hazard (he) captures both the probability of a biological response to EMF exposure (which may be fairly high) and the probability that this biological response leads to a significant number of health effects (which may be fairly low). Since experts disagree widely about this probability, we will investigate its effect over a wide range, from he=0 to he=0.50, with a base case of he=0.10.

The probability of a research breakthrough, given a hazard (q) depends on the amount of research funding per year, and the number of years of research. Considering that 20 years of research has not created a research breakthrough, it is not very likely that the next year, or even the next five years will produce such a breakthrough, even if there is a health hazard. In addition, the incremental probability of a positive breakthrough should be marginally decreasing as time goes by. To capture these thoughts, we modeled the probability of a positive breakthrough, given a health hazard by the following exponential probability density function f and cumulative distribution F:

$$f(t) = -\lambda \exp\{-\lambda(R)\, t)\}, \quad (1)$$

$$F(t) = 1-\exp\{-\lambda(R)\, t\}, \quad (2)$$

where t is the time to a breakthrough, λ is the parameter of the exponential distribution, which depends on R, the level of research funding.

This exponential distribution is generally considered to be appropriate for waiting time problems. The key issue is, of course, how the parameter λ depends on the level of research funding R. For this assessment it is useful to know that the expected time E(t) to a breakthrough is $1/\lambda$. Thus, if λ=.05, one would expect that it would take 20 years to a research breakthrough, if there is a health hazard.

Table 1 shows some rough estimates of the expected time to a breakthrough as a function of research funding, which are based on informal discussions with EMF researchers. At the minimum funding level, provided by regular competitive funding sources like the National Science Foundation, the expected time would be large, e.g., 40 years. Even at funding level close to the current level (e.g., $10 million/year), the expected time would be significant. It would not be surprising, if another 20 years would pass without a research breakthrough. By significantly increasing the funding level to $100 million per year, the time to breakthrough may be cut to 10 years, but there are limits to speeding up research, imposed by set-up costs and research inertia. Thus, even with an extraordinary research budget of $ 1 billion per year, it seems not very likely that one could expect any faster resolution of the EMF issue than 5 years.

Table 1: Relationship Between Annual Research Funding and the Probability of a Breakthough Given an EMF Hazard

Annual Research Funding (Millions)	**Expected Number of Years** (Estimate)	l (Estimate)	l (Calculated)	**p(Breakthrough)** 1 Year	10 Years
$ 1	40	0.025	0.025	0.02	0.22
$ 10	20	0.050	0.065	0.06	0.48
$ 100	10	0.100	0.105	0.10	0.65
$ 1,000	5	0.200	0.145	0.13	0.77

Note: Calculated $\lambda(R) = 0.04*\log(R) + 0.025$

These rough judgments about the expected time to a positive breakthrough translate into corresponding values of λ, as shown in Table 1. Based on the estimated relationship between λ and R, a function $\lambda(R)$ was fitted as

$$\lambda(R) = 0.04 \log(R) + .025. \qquad (3)$$

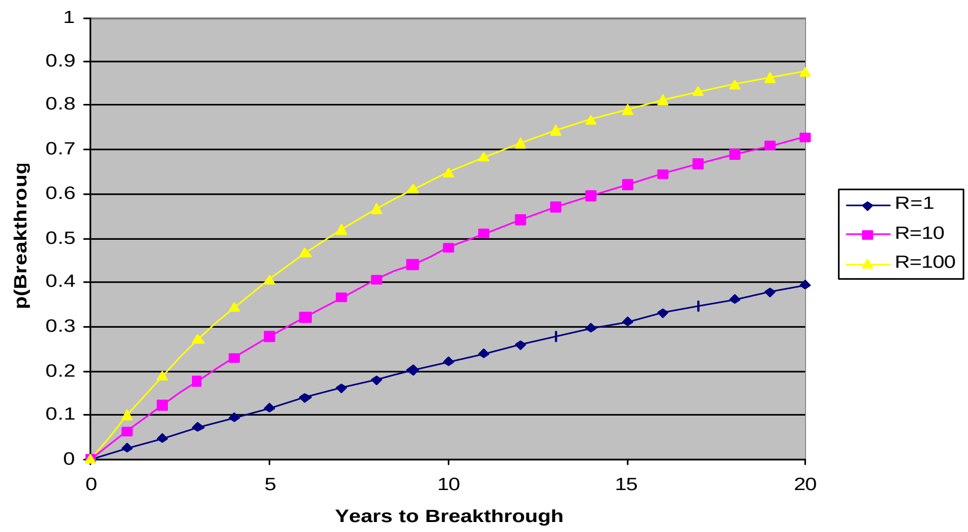
As seen in Table 1, the calculated values of this function correspond fairly closely to the estimated ones in the range of R between $ 1 million and $1 billion. This function was then used to calculate the probability of a positive breakthrough within t years as

$$F(t) = 1\text{-}\exp\{-(0.04 \log(R) + .025)\, t\}. \qquad (4)$$

Examples of this function for several values of R are shown in Figure 2.

The decision tree model uses the parameter $q(t)=F(t)=1-\exp\{-(0.04\ R + 0.025)\ t\}$, the probability that a positive research breakthrough is achieved within t years of funding. We frequently work with t=1 and the probability q=q(1) that the first year of research will resolve whether EMFs are a hazard. Table 1 shows some values of q for t=1 and t=10. Corresponding to q(t), the probability of a positive breakthrough, is r(t), the probability of a negative breakthrough. Since it is harder to prove a negative, we defined r as q/2.

Figure 2: Breakthrough Probability



With these inputs, the unconditional probabilities of research outcomes (pr for positive research, nr for negative research, 1-pr-nr for inconclusive research) and the conditional probabilities of a health hazard, given research outcomes (hir for a health hazard given inconclusive research, 1-hir for no health hazard given inconclusive research) can be calculated as follows:

$$pr=he*q, \qquad (5a)$$

$$nr=(1-he)*(q/2), \qquad (5b)$$

$$ir=1-pr-nr, \qquad (5c)$$

$$hir=he*(1-q)/ir. \qquad (5d)$$

Since q is a function of the research funding level R, the resulting marginal and conditional probabilities will differ for the decision of special research funding for EMF and no special research funding.

Consequences. At the end of each path through the decision tree in Figure 1, one needs to take stock of the various consequences that this path produced. The model considers six types of consequences:

- R: Annual EMF research funding ($ millions per year)
- H: Annual fatalities due to EMF (number per year)
- I: Annual illnesses due to EMF (number per year)
- M: Cost of mitigation to eliminate health effects ($ millions),
- P: Value of appreciated property due to mitigation ($ millions),
- S: Annual cost of "social strife" of the EMF controversy ($ millions per year).

Base case estimates and ranges for these consequences are shown in Table 2 and discussed below.

Table 2: Base Case Estimates and Ranges for Consequences

Variable	Description	Low	Base	High
R	Research Funding (in $ millions/year)	$1	**$25**	$1,000
H	Number of Fatalities/Year Given Hazard	100	**1,000**	10,000
I	Number if Illnesses/Year Given Hazard	500	**5,000**	50,000
M	Mitigation Cost (in $ millions)	$5,000	**$50,000**	$500,000
P	Property Value Appreciation (in $ millions)	$0	**($30,000)**	($50,000)
S	Social Strife Cost (in $ millions/year)	$0	**$100**	$1,000

Note: All consequences are expressed as costs, except property values, which are a gain.

Annual research funding peaked at about $25 million in the US, and it will likely decline over the next few years. The minimum research funding would be about $1 million, which would be expected from agencies like NSF and NIH. It is hard to imagine funding at a level of $100 million/year or above. The upper range was included in the analysis primarily to explore where research funding loses marginal benefits.

The number of annual fatalities due to EMF will be zero for all paths in the decision tree that end up with “no health hazard” or with “mitigation”. At the high end, it is conceivable that there would be thousands of fatalities. Assuming, for example, that EMF is a serious health hazard that doubles the base rate fatality risk of all implicated cancers for people living near power lines and that 2% of the population live near such powerlines, the total excess fatality rate would be 5,000/year.

Illnesses include curable breast cancer or other curable cancers and non-fatal diseases like Alzheimer’s disease. Illnesses are counted in the model as multiples of fatalities. In the base case we assume that there are five illnesses for each fatality. Thus, illnesses could be as high as 50,000 cases per year.

Mitigation costs depend strongly on the scenarios that define the number of health effects, the mechanisms of a possible EMF-health link, and the knowledge gained by a research breakthrough. For example, if a positive research breakthrough establishes that there are about 1,000 fatalities due to a specific causal mechanism, the mitigation costs would likely consist of selectively reducing ground currents in homes and locally undergrounding transmission and distribution lines, at a cost in the tens of billions. If, on the other hand, the research establishes that there are 10,000 fatalities due to an ill specified mechanism, nothing short of massive undergrounding and elimination of ground currents would do the job, possible at a costs of hundreds of billions.

Powerlines, especially transmission lines, have been associated with reduced property values (Gregory and von Winterfeldt, 1996). Undergrounding these lines will therefore increase property values, even if EMF was not an issue. Assuming that 2% of some 100 million homes in the US are close enough to transmission or distribution lines to warrant undergrounding, and further assuming an average home value of $150,000, a ten percent appreciation in property values would create $30 billion in property appreciation as a side benefit of undergrounding.

The EMF controversy has produced substantial social strife through law suits, controversies about the siting of new powerlines, etc. Continued research is likely to provide fuel for this strife. It is possible, on the other hand, that eliminating the special research funds will reduce social strife. In the model, we allocate somewhere from no cost of social strife to $100 million/year for the branches that involve continued research, and a corresponding amount reduced by a parametric factor a (base case: a=0.90) for the branches that involve no special research.

Table 3 shows the base case estimates of consequences for all end-nodes of the decision tree in Figure 1. Note that the only differences between "Special EMF Research" and "No Special EMF Research" are the level of research funding (R) and the social strife cost (S).

Table 3: Base Case Estimates of Consequences at Each End Node of the Decision Tree

	R ($mio/yr.)	H (Deaths)	I (Illnesses)	M ($mio)	P ($mio)	S ($mio/yr.)
Special EMF Research						
Positive Breakthrough - Mitigate	$25	0	0	$50,000	($30,000)	$0
Inconcl. Research - Mitigate	$25	0	0	$50,000	($30,000)	$0
Inconcl. Research - Don't Mitigate - Hazard	$25	1,000	5,000	$0	$0	$100
Inconclusive Research - Don't Mitigate - No Hazard	$25	0	0	$0	$0	$100
Negative Research Breakthrough - Don't Mitigate	$25	0	0	$0	($30,000)	$0
No Special EMF Research						
Positive Breakthrough - Mitigate	$1	0	0	$50,000	($30,000)	$0
Inconcl. Research - Mitigate	$1	0	0	$50,000	($30,000)	$0
Inconcl. Research - Don't Mitigate - Hazard	$1	1,000	5,000	$0	$0	$90
Inconclusive Research - Don't Mitigate - No Hazard	$1	0	0	$0	$0	$90
Negative Reseaerch Breakthrough - Don't Mitigate	$1	0	0	$0	($30,000)	$0

Tradeoffs and Discounting. To make all consequences commensurate, they are transformed into 1998 dollars. Mitigation costs and property value appreciation are already counted as 1998 dollars. Research funds and social strife costs are counted in annual dollars. To make these annual dollar streams of research and social strife costs commensurable with the fixed 1998 costs, we discount the cost streams using a rate d, which varies from 0% to 5%. For reference, the federal Office of Management and Budget used a net discount rate of 3.9% for government projects starting in 1996. As a base case, we used 4%.

Health consequences are counted as the annual number of fatalities due to EMF exposure. We first transformed the fatalities into an equivalent dollar cost, using a value of life (VOL) of $5 million per fatality as a base case. This equivalent cost is in the mid-range of public expenses for life-savings programs (see Tengs et al., 1995), which vary from a low of tens of thousands per fatality (for example, for highway safety programs) to tens of millions per fatality (for example, for nuclear power safety).

Next, we discounted the equivalent costs of a fatality by d%. An infinite stream of costs c/year, discounted at d% has a net present value of c/d which is the amount used for 1998 costs. For example, assuming 1,000 fatalities per year at $ 5 million per fatality, the annual equivalent costs are $5 billion. The infinite stream of $5 billion per year discounted at 4% corresponds to $125 billion in 1998 net present value.

It is important to point out that we are not discounting fatalities, but the expenditures to save lives. The choice between saving a life today vs. in ten years is very hard, but the choice between spending $5 million today to save a life today vs. spending $5 million today to save a life in twenty years is easy. Clearly, the $5 million today could be used as an investment to create twice as much money (in real terms at a 4% net growth rate), and thus save two lives in 20 years.

The value of an illness (VOI) is $200,000 in the base case. This cost corresponds roughly to the estimated social costs of one case of Alzheimer’s disease. The equivalent costs of the annual number of illnesses are discounted at 4% to calculated an equivalent net present value.

With these ground rules, and using the base cases of Table 3, we now can convert the set of five consequences at the end of each path through the decision tree into 1998 dollars and simply sum up the costs to a total equivalent cost. The formula for calculating the total equivalent cost X for the first year of research funding is:

$$X = R + H{*}VOL/d + I{*}VOI/d + M + P + S/d. \qquad (6)$$

Results

The procedure to calculate the expected equivalent cost of the two alternatives at the root of the decision tree is called “averaging out and folding back” (Raiffa, 1968). Beginning at the right hand side of the decision tree, the expected cost (EC) is calculated by taking the probability-weighted average of the consequences at each chance node (circle). At each decision node (square), the minimum expected cost is substituted for the actual cost foreseen at that node.

For example, in Figure 3 the equivalent expected cost of $16,522 million for the decision node “Don’t Mitigate” following special funding and inconclusive research was calculated as follows:

EC (Don’t Mitigate) = 0.09331*$152,525+0.90669*$2,525 = $16,522 (in millions).

This calculated expected cost is less that the expected cost of “Mitigation” at this decision node, and, it is therefore substituted as the equivalent cost at this node. The expected cost for the node “Special EMF Research” is calculated as

EC(Special EMF Research) = 0.00777*$20,025 + 0.098834*$16,522 +
+ 0.00389*(-$29,975) = $16,369.

Figure 3 shows the expected cost at each node, using the averaging out and folding back procedure. At the root node, it shows that the decision to fund research at $25 million per year is better by about $500 million than the decision to reduce funding to $1 million of “non-special” research.

The reason for this high value of research is the increased probability of a positive or negative breakthrough. Increasing research funds increase the probabilities of positive or negative breakthroughs and reduce the probability of inconclusive research and, by implication, the probability of a health effect, given inconclusive research. While these changes in probabilities are small, they operate on very large stakes, so that the expected cost differences are still very large in comparison to the cost of research.

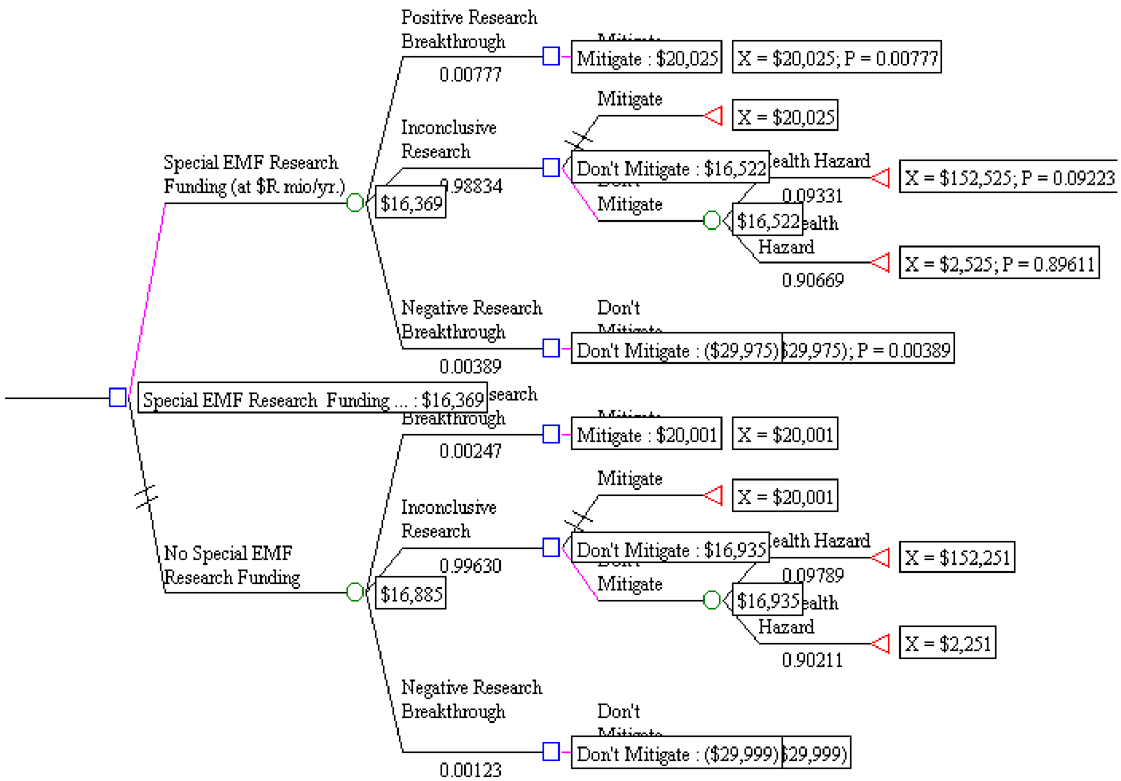


Figure 3: The Solved Decision Tree to Determine the Value of EMF Research

Note that when research is inconclusive, the best action is not to mitigate. The expected cost of this action is smaller for the "Special Research Funding" subtree than for the "No Special Research Funding" subtree.

Figure 4 shows how the expected value of the decision to provide special funding for EMF research varies with the amount of special research funding. The optimal amount (least expected cost) is about $200 million/year. Research funding below about $13 million/year is not worth it, because it does not have sufficient effect on the probability of a breakthrough. Research funding above about $1,200 is not worth it, because it would exceed the marginal benefits of reducing the health and other social costs of learning about the research outcomes.

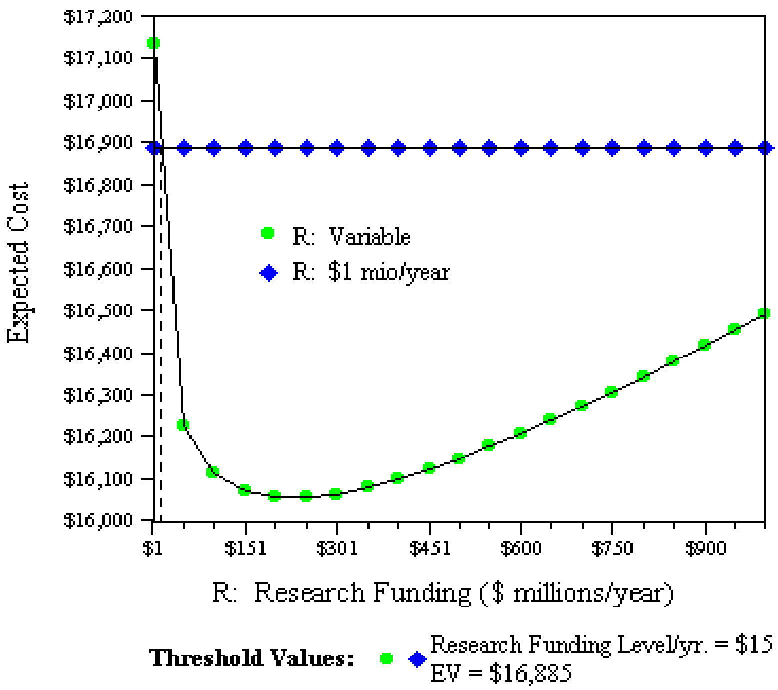


Figure 4: Sensitivity Analysis on Research Funding/yr. (Base Case)

Figure 5 shows how the same results for the low-consequence scenario (see Table 2). Even in this case, the optimal funding level is about $16 million. Figure 6 shows the results for the high-consequence scenario. In this case, the optimum research funding level exceeds $1 billion per year. Note that in all three scenarios the largest value of research is obtained from the first millions.

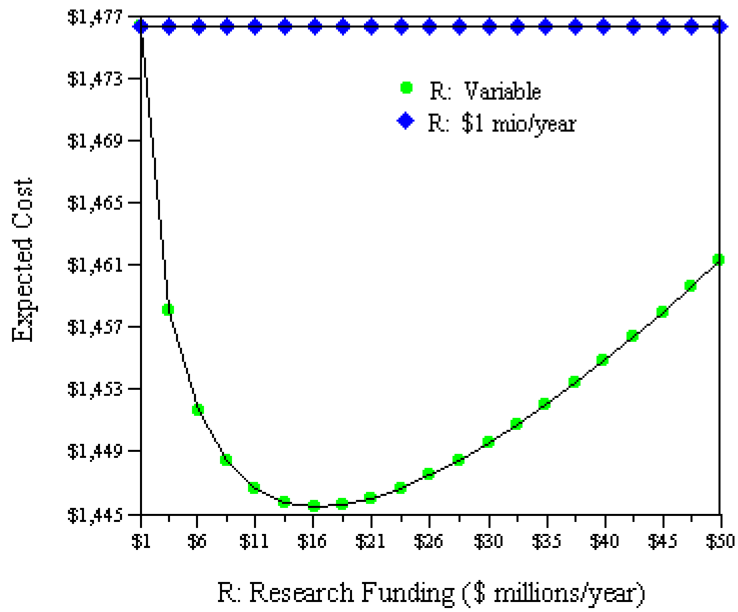


Figure 5: Sensitivity Analysis on Research Funding Level/yr. (Low Case)

Table 4 summarizes the optimal funding level for the three scenarios described in Figures 4-6 in the diagonal cells and six scenarios summarized in the "off-diagonal" cells. In three of these "off diagonal" scenarios, it is not worth spending special funds on EMF research:

- when health effects are small (100 fatalities and 500 illnesses per year) and the mitigation costs are at the base case ($50 billion),

- when health effects are small (100 fatalities and 500 illnesses per year) and mitigation costs are high ($500 billion),

- when health effects are at the base case rate (1000 fatalities and 5000 illnesses per year) and the mitigation costs are high ($500 billion).

In these three scenarios the mitigation costs exceed the health costs and, as a result, one would never mitigate, even if there is a positive research breakthrough. In the other "off-diagonal" scenarios, the optimal research funding ranges from a low of $3.5 million to $40 million.

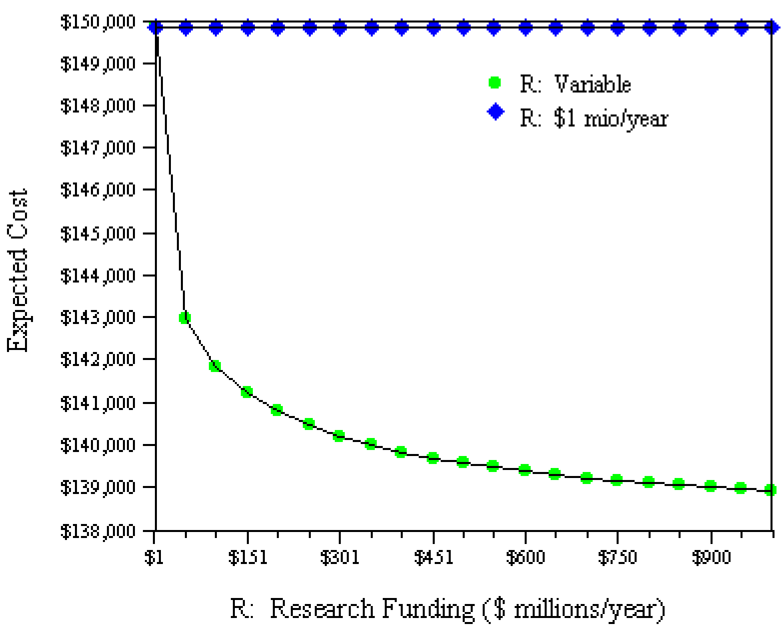


Figure 6: Sensitivity Analysis on Research Funding Level/yr. (High Case)

While we include the off-diagonal scenarios, they are clearly not very likely. For example, it is hard to imagine a positive research breakthrough identifying a mechanism leading from EMF exposure to 100 fatalities and 500 illnesses, yet requiring $50 or even $500 billion of mitigation costs. Similarly, it is hard to imagine a positive breakthrough with 10,000 fatalities and 50,000 illnesses that is due to a mechanism that can be fixed for $5 billion.

Table 4: Optimal EMF Funding Level As a Function of Health Effects and Mitigation Costs

		Health Effects		
		Low	Medium	High
Mitigation Cost	Low	$16	$4	$3.5
	Medium	$0	$200	$40
	High	$0	$0	$1,200

Entries are in $ millions per year

Sensitivity Analyses

The comparison of the base case, high, and low consequence scenarios revealed that the value of research increases roughly with the increase in health effects and mitigation costs. To further investigate the joint effect of these two variables, a two-way sensitivity analysis was conducted as shown in Figure 7. This figure shows that special research of $25 million per year is worth while unless the cost of mitigation is about as high as the equivalent cost of health effects, or if the cost of mitigation is very low.

One would also expect that a low prior probability of a health hazard (he) would reduce the value of EMF research. In Figure 8, we plot a two-way sensitivity analysis which shows that for he<.03 the "No Special Research" option is preferred, pretty much independently of funding level. Above he=0.03, however, special research funding is preferred, even at a very low funding level. This analysis shows the importance of the prior probability of an EMF hazard (in this case, a hazard involving only 1,000 health effects) on the decision to fund EMF research.

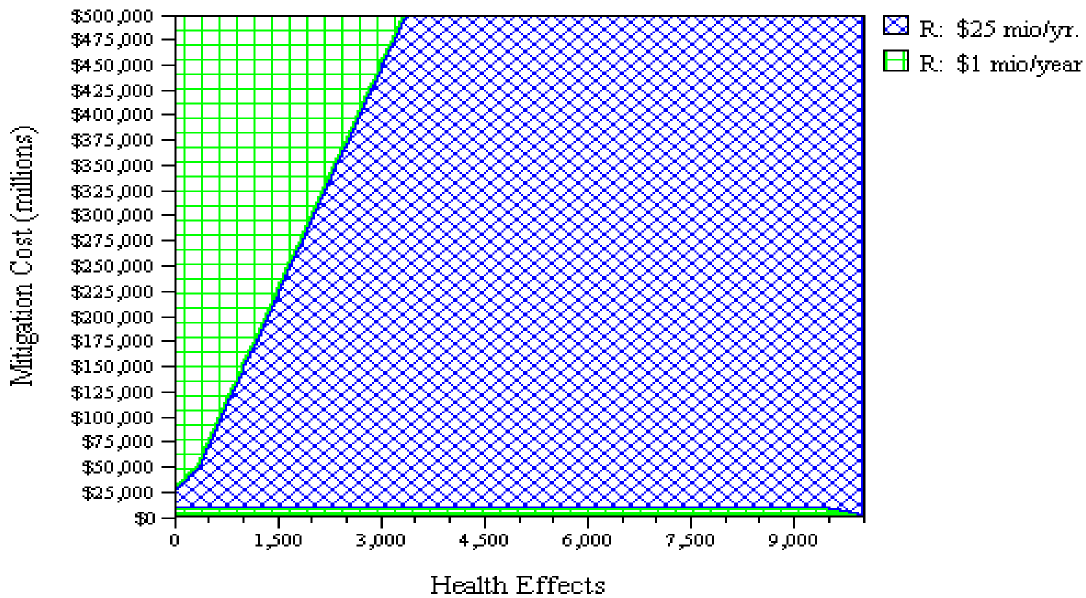


Figure 7: Sensitivity Analysis on Health Effects and Mitigation Cost

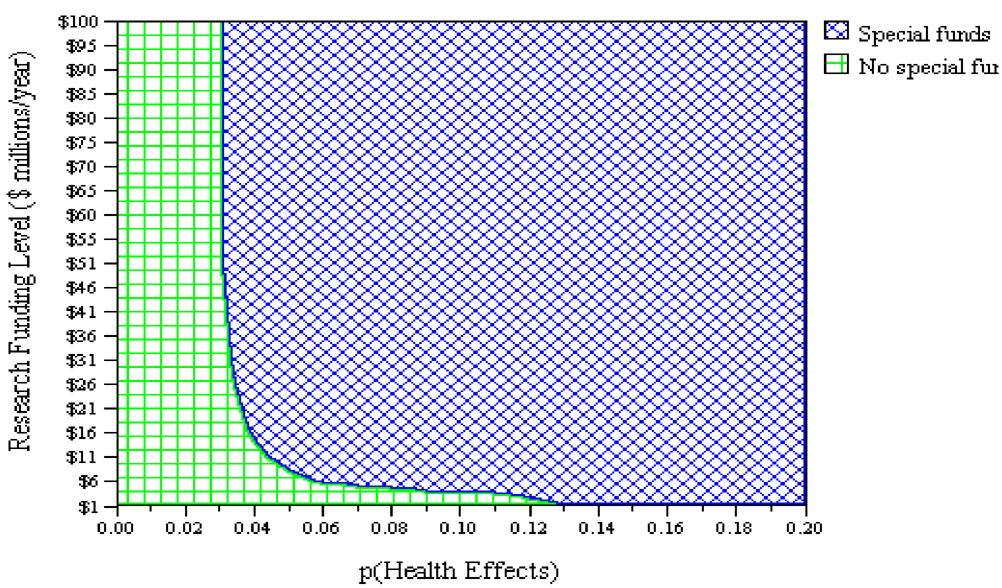


Figure 8: Sensitivity Analysis on p(Health Effects) and Research Funding Level/yr.

Since it is likely that the outcome of research remains inconclusive, the difference in social strife (S) created by a significant amount of research vs. a modest amount of research may become important. Figure 9 shows that special EMF research is preferred, unless the strife reduction is more than about 40%.

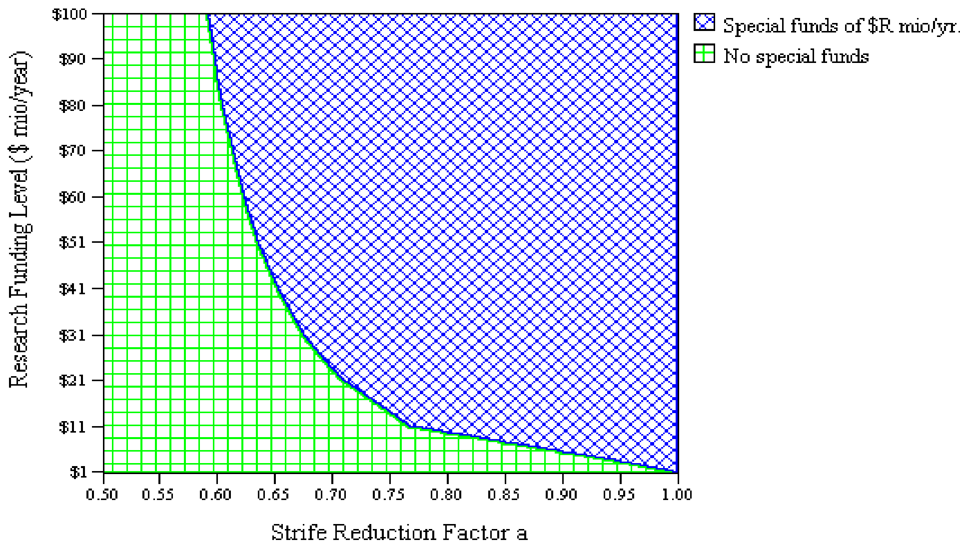


Figure 9: Sensitivity Analysis on Strife Reduction Factor and Research Funding Level/yr.

The model assumes that the mitigation costs are the same in the case of a positive breakthrough as in the case of inconclusive research. However, it is much more likely, that the positive research breakthrough will provide information that will substantially reduce mitigation costs. In particular, information about the operative exposure metric and biological mechanism will affect mitigation costs. For example, if the breakthrough proves that EMF exposure is a hazard only above 10 mG, mitigation costs could be in the low billions. The effect of assigning a higher mitigation cost to the "inconclusive research" branch is that it makes mitigation at that node even less attractive than non-mitigation (the preferred alternative in most scenarios). Thus, the value of research will not change as a result of this increase in mitigation cost.

One might argue that eliminating special funds for EMF research may have additional social costs, if a breakthrough is achieved surreptitiously with the regular funds for this type of research. Adding this type of penalty will only increase the value of research, and thus the numbers in Table 4. For example, adding a $100 billion “penalty” for a positive breakthrough after special research has been terminated increases the optimum research funding level in the base case from about $200 million/year to about $250 million/year. This increase is fairly modest, in spite of the large penalty, because the probability of a positive breakthrough is small with no special research funding.

The findings will also be sensitive to the function $\lambda(R)$ that relates annual research funding to the expected time that it takes to achieve a breakthrough, if there is a hazard. The base case function assumes an expected time of 20 years at a funding level of $10 million per year, and, correspondingly, 40 years, if there is no hazard. It is hard to imagine any slower resolution of the EMF issue. Changing this function to reflect a faster resolution of the research issue will increase the value of research in all calculations.

Conclusion

Given that 20 years of EMF research has not produced conclusive results, it is perhaps surprising to find that it is worth spending considerable amounts of money on additional research. The reason for this high value of EMF research is, however, fairly easy to understand: As long as the possibility of large numbers of health effects remains, and as long as mitigation is less costly than the health effects, even a small probability of resolving the EMF issue has enormous payoffs. As a rough rule of thumb, the value of research is proportional to the probability of resolving the EMF issue times the difference between health and other social costs and mitigation costs. As long as the difference between the health and social costs and the mitigation cost are in the billions of dollars, even a very small probability of resolving the issue produces large expected cost reductions.

Of course, whenever mitigation costs exceed the health and social costs, or when they are very close, the value of research diminishes or becomes zero. Table 4 and Figure 8 illustrate this point. However, we make the argument that these scenarios are quite unlikely.

In addition to the consequences of the research funding decision, two model parameters influenced the value of research strongly. The first parameter is the prior probability of a health hazard. As prior probabilities decrease towards 0.03, the value of research decreases to zero, below 0.03 it remains at zero. It would be interesting to poll EMF researchers to determine the current range of prior probabilities of a hazard. Informal discussions suggest that this probability is substantially higher than 3%.

The second parameter is the strife reduction factor, which indicates how much less social strife is created with no special research vs. special research at a significant funding level. The value of research decreases with this factor and approaches zero when the strife reduction of stopping the research funding is substantial (about 60-70% of the strife generated with special EMF funding). While this factor has a major impact on the value of research, it is also a very speculative item. It is quite unclear, how the much the social strife of doing special EMF research costs, and it is even less clear, by how much this cost can be reduced by stopping the research. One might even argue that the social strife is increased by stopping special EMF research, for example, by leaving the EMF field open to less qualified scientists and occasional dramatic findings that are not carefully reproduced.

On balance, the robust conclusions of the decision analysis presented in this paper is that special EMF research funding should be continued, and should possibly increased from current levels. As long as the stakes are high and the chances of a hazard are in the order of 10% or higher, it is clearly worth to pursue the elusive research breakthrough.

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